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ON THE ELECTRONS IN THE COMPOSITION OF PRIMARY COSMIC RAYS

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OF PRIMARY COSMIC RAYS

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According to available experimental data, of which we will speak later, no electrons have been found in the composition of cosmic rays which reach the Earth. Therefore, it may seem at first glance that there is no reason to be particularly interested in the problem of the electron component of primary cosmic rays i.e. the rays which reach the upper limits of the atmosphere. However, this is not so. First, the absence of electrons in the primary component near the Earth is a very significant fact which must be taken into account and explained by every theory in the origin of cosmic rays. Second, data on galactic radio emanations now affords a basis for assuming that the interstellar space of our Galaxy contains a considerable number of relativistic electrons, comparable to the number of relativistic protons, but with a mean energy less than that of the protons. (Most electrons have an energy $E < 10^9$ ev.) In our opinion, these two facts fully justify the discussion of the problem of the electron component of primary cosmic rays undertaken below.

In section 1, data are presented on the electrons in the cosmic rays which reach the top of the Earth's atmosphere. There is also a discussion here of the question of the gap in the spectrum of the primary cosmic rays at high geomagnetic latitudes in connection with the problem of the dipole magnetic moment of the Sun or solar system. Further, in section 2 the problem of galactic radio emanations is discussed as a source of information on the relativistic electrons in interstellar space. Section 3 compares the energy losses of electrons in interstellar space which are connected with ionization and radiation losses, decelerating radiation in the interstellar magnetic fields, and the reverse Compton effect on interstellar photons. Data on a possible mechanism, leading to the acceleration of electrons in interstellar space, are also presented in this section. Finally, in section 4, as a result of comparing all the material there ~~is~~ a discussion of the question of the origin of cosmic rays and, in particular, of cosmic electrons.

1. Experimental Data on Electrons at the Upper Limits of the Atmosphere. The Gap in the Spectrum of Cosmic Rays at High Latitudes

According to the latest available data [1], the number of primary particles of the soft component (electrons, positrons, photons) with an energy $E \geqslant 1.1 \cdot 10^{9}$ ev does not exceed 0.6% of all primary particles with the energy of more than approximately 10^{9} ev. Corresponding measurements were made by means of balloon-lifted cloud chamber at the geomagnetic latitude of 55° (in the following text, "latitude" means always geomagnetic latitude). This result does not contradict the estimations made in earlier works [2,3] which we are not going to analyze here in more detail. It can be noted that the vertical intensity of all primary particles (of which protons account for approximately 80%), at the latitude of 55° N is equal to approximately $I \simeq 0.22 \frac{\text{particles}}{\text{cm}^2 \cdot \text{sec.}}$ steradian

At the latitude of 58° N $I \simeq 0.29 \pm 0.03 \frac{\text{particles}}{\text{cm}^2 \cdot \text{sec. steradian}}$ (rocket data [4]).

This intensity, apparently, does not increase significantly at higher altitudes (see below). In the hypothesis, concerning the isotropy of primary particles, their concentration $N \simeq \frac{4\pi}{c} I \simeq \frac{4\pi}{c} 0.29 \approx 1.2 \times 10^{-10}$ cm^{-3}. At the geomagnetic equator [4], $I = 0.028 \pm 0.004 \frac{\text{particles}}{\text{cm}^2 \cdot \text{sec. steradian}}$.

Thus, approximately 9/10 of all primary particles posses an energy in the range of $1.2 \times 10^{8} \div 14.8 \cdot 10^{8}$ ev, corresponding to the permissible energies at latitudes 58° and 0°

For the sake of convenience, Table 1 gives the minimum pulse and the corresponding Kinetic energies for electrons and protons which can reach in the vertical direction a point with geomagnetic latitude λ (calculation has been made according to the formula $CP_{min.vert.} \simeq 14.8 \div 10^{8} \cos^{4} \lambda$ ev).

According to data [5,6], at the latitude 69°N $I = 0.25 \pm 0.02 \frac{\text{particles}}{\text{cm}^2 \cdot \text{sec. steradian}}$ (at the altitude which corresponds to $16 \div 20$ g/cm^2 from the top of the atmosphere). Comparison of these data with those refering to the altitude of 58°N (see above), leads to the conclusion that the spectrum of the primary particles is cut off at approximately the latitude of 58°N, i.e. for a proton energy $E_{kin} \simeq 5 \cdot 10^{8}$ ev and an electron energy $E = 1.2 \cdot 10^{9}$ ev. Since the measurements have been made by different authors using different methods, no definite conclusion on the presence of a gap in the spectrum can yet be made (Note 1), even though such con-

Table 1.

Dependence of the Threshold Pulse and Kinetic Energy of Electrons and Protons on the Geomagnetic Latitude

Geomagnetic Latitude	$CP_{min.}$ vert ev	E_{kin}, ev	
		electrons	protons
78° 30' N (geograph. pole)	$2,3 \cdot 10^{7}$	$2,3 \cdot 10^{7}$	$0,3 \cdot 10^{6}$
74° N (Spitzbergon, Franz-Josef Land)	$8,6 \cdot 10^{7}$	$8,6 \cdot 10^{7}$	$4 \cdot 10^{6}$
69° N	$2,5 \cdot 10^{8}$	$2,5 \cdot 10^{8}$	$3,2 \cdot 10^{7}$
63°30' N (Murmansk)	$5,9 \cdot 10^{8}$	$5,9 \cdot 10^{8}$	$1,72 \cdot 10^{8}$
58° N	$1,2 \cdot 10^{9}$	$1,2 \cdot 10^{9}$	$5,6 \cdot 10^{8}$
52° N	$2,1 \cdot 10^{9}$	$2,1 \cdot 10^{9}$	$1,4 \cdot 10^{9}$
0°	$14,9 \cdot 10^{9}$	$14,9 \cdot 10^{9}$	$14 \cdot 10^{9}$

clusions appear to be very probable (Note 2). In any case, even is there is no gap in the spectrum, it can be stated that at latitudes above 58^o the spectrum becomes considerably flatter, than at lower latitudes (Note 3). In the range 2.10^8 ev $\leqslant pc \leqslant 15.10^9$ ev $(0^o \leqslant \lambda \leqslant 52^o)$ the spectrum is of the type $N(E)dE = K - E^{r}dE$, where $r = 1.9 \div 2.1$ [4,7]. In the region of greater energies ($E > 10^{12}$ ev), according to the data on extensive atmospheric showers, $r = 2.7$. The overall view of the integral spectrum is clearly seen in Fig. 1 (the plotted curve is $\int_{E}^{\infty} N(E)dE$; Kinetic energy E_{kin} is marked on the abscissa. As already indicated, with $cp < 10^8$ ev, the spectrum is either cut off, i.e. the particles with $cp < 10^8$ do not reach the Earth's orbit at all, or the differential spectrum has a sharp maximum with $cp \backsim 10^8$ ev, and thus the indicator $r = 0$, when cp is lower and a gradual spectrum is used.

(Note 1): The works [35,36] present data which indicate, with a great degree of probibility, the existence of high-latitude cutoff.

(Note 2): If we agree that all possible increase in the number of particles between latitudes 58^o and 69^o is due to electrons, then, taking the values [4,5] with the maximum of indicated errors, we obtain for the number of electrons in the range of $2.5 \cdot 10^8 < E < 1.2 \cdot 10^8$ the value of 3.7% of the entire flux at these altitudes (in [4] $I_{58^o} 0.29 \pm 0.03$; in [5], according to [6] $I_{69^o} = 0.25 \pm 0.02$, and thus, $\Delta I = I_{69^o max.} - I_{58^o min.} = 0.01$ and $\frac{\Delta I}{I} = 3.7\%$).

(Note 3): It may be noted that calculations are usually made with the assumption that the field of the Earth is a field of a dipole with the moment $8.1 \cdot 10^{25}$ gauss $\cdot cm^3$, situated in the Earth's center, while the Northern magnetic pole axis has coordinates 78°30' N, 69° W. Actually, this assumption is not strictly precise, but the error introduced, evidently, is small. The formula used in the text for $cp_{min\ vert}$ (See [8] is also approximate.

The difference between the two cases may be very small from the point of view of spectrum form, but it can be very significant from the point of view of interpretation. In the first case (cutoff), it can hardly be doubted that the absence of particles with small energies near the Earth is due not to their absence in interstellar space, but to the action of a certain magnetic field. Usually, the solar dipole field is regarded as such a magnetic field. In the second case, when the low-energy particles are still present (even though only in small numbers), certain considerations, based on the Louisville theory (see for example [87]), lead to the conclusion (Note 1) that the number of low-energy particles ($cp < 10^9$ ev) in the interstellar space is very small (their density must be the same, as at the top of the atmosphere) (Note 2).

(Note 1) It is assumed that the particles move only within the magnetic field; this assumption seems to be justified.

(Note 2) It may be noted that the protons with $E_{kin} \approx 3.10^7$ ev ($\lambda = 69^o$) have the velocity $v = \frac{c}{4}$. Therefore, with the given value of the intensity of particles I, their density $N = \frac{4\pi I}{v}$ will be approximately four times greater, than in the case of relativistic particles which include the electrons with $E_{kin} \approx 2.5 \cdot 10^8$ ($\lambda - 69^o$). On the basis of this example, also taking into consideration that actual measurements were made with the protons with $E_{kin} > (1.3 \div 1.7) . 10^8$ ev (depth on the order of $16 \div 20$ g/cm^2 of air equivalent), it becomes clear that our conclusions remain practically unchanged, although at $\lambda > 70^o$ the difference between v and c may be very substantial.

The existing notions on the origin of cosmic rays and their motion in the interstellar space do not provide a basis for making an entirely sure choice between the two aforementioned possibilities. This problem must be solved primarily by experimental investigation of the spectrum at high latitudes (the main question is, whether a sharp cutoff in the spectrum occurs; see above.) However, we may say that the assumption of the absence of a considerable number of particles with $cp < 10^9$ ev in the Galaxy in the region of the Sun (second case) appears to be very far fetched and hardly probable. Actually, the low-energy particles will be absent, if they are not created in the Galaxy at all, or if the primary sources of these particles are concentrated in the center of the Galaxy, and the softer particles cannot reach us. [9]. The first assumption is very artificial, since there is no reason for believing that primary sources would furnish only particles with $cp > 10^9$ ev i.e. with E_{kin} $5 \cdot 10^8$ ev for protons. The second assumption is also without foundation, because the most probable primary sources, the supernova stars (see section 4), form a flat, and not a spherical subsystem with a small radius. Moreover, in [9], in accordance with [10], it is accepted that the value $\ell \sim 10^8$ is a mean length of the path in the stellar magnetic field, while in the framework of the Fermi mechanism [10] it would be more correct to chose the value $\ell \sim 10^{19}$ (see [11]. From the point of view of [9], this moment is unfavorable. Still more difficult, if ever possible, is the explanation of the extinction of the spectrum in the field $cp < 10^9$ ev for electrons which have smaller ionization losses. Finally, the data on the galactic radiation, which will be discussed in Section 2, testify to the fact that, in the direction of the galactic pole, there is a considerable number of electrons with an energy $cp < 10^9$ ev. It follows directly from this, that the absence of electrons on Earth must be connected with some kind of mechanism for cutting off the spectrum. It is most natural to assume that the cutoff in the spectrum appears within the limits of the solar system, i.e. that precisely the second case occurs.

The absence of particles with $cp < 10^9$ ev was explained until recently /8/ by a "magnetic cutoff", connected with the effect of the solar magnetic dipole-moment. Since the Earth is situated close to the presumed heliomagnetic equator, the smallest pulse of particles able to reach the Earth in any direction, according to /8/, is equal to

$$cp_o = \frac{eM_\odot}{R^2} = 1{,}36 \cdot 10^{-24} M_\odot$$

where $M_\odot$ is the solar magnetic moment and R is the radius of the Earth's orbit (in the last expression, measuring $M_\odot$ in gauss.cm^3, we obtain cp_o in electron-volts). The Earth's orbit is inaccessible to particles in any direction, if their impulse is less than the pulse p_{min}

$$cp_{min} = \frac{cp_o}{5{,}84} = 2{,}33 \cdot 10^{-25} M_\odot$$

$$M_\odot (\text{rayce} \cdot cm^3) = 4{,}3 \cdot 10^{24} cp_{min} (2)$$

The magnetic moment (2) corresponds to the field on the solar pole which is equal ($r_\odot = 7 \cdot 10^{10}$):

$$H_{II\odot} = \frac{2M_\odot}{r^3_\odot} = 2{,}5 \cdot 10^{-8} cp_{min}$$

When $p < p_{min}$, the particles do not reach the Earth at all; when $p < p_o$, particles reach it from all directions, while with $p_{min} < p < p_o$, only particles moving from infinity in certain directions reach the Earth. It would seem, therefore, that, due to the Earth's rotation, there should occur diurnal variations of cosmic radiation. According to /12/, these variations should be considerable. Their absence in reality testifies, from this point of view, to the absence of the effect of a solar magnetic field. However, more precise calculations /13/ lead to the conclusion that the absence of variations within the limits of the attained accuracy of measurements is not incompatible with the presence of a solar moment $M_\odot \leqslant 6.5 \cdot 10^{33}$ ($H_{\text{ц}\odot} \leqslant$ oersted). The absence of variations can be explained by the fact that the particles with pulses in the range $p_{min} < p < p_o$, for various reasons, get into periodical orbits; as a result, the particles with $p > p_{min}$ arrive at the Earth from all directions (see /12, 13, 21/). Assuming $cp_{min} = 10^9$ ev, we obtain

$$M_\odot = 4{,}3 \cdot 10^{33}; \quad H_{II\,\odot} = 25 \text{ oersted}$$

Having in mind the insufficient accuracy of experimental data, it may be considered that the cutoff occurs even when $cp \leqslant 1.5 \cdot 10^9$, which corresponds to the field $H_{II\,\odot} \leqslant 40$. Thus, for the explanation of the observed cutoff, a field $H_{II\,\odot} \leqslant 25$ oersted is necessary (we have already mentioned that these data need more precision). On the other hand, data on the cosmic rays do not contradict the presence of a field $H_{II\odot}$, reaching up to 40 oersted. At the same time, astrophysical data indicate that, at least at present, $H_{II\odot} < 2 \div 5$ oersted. However, according to [14] existing methods for measuring the general solar magnetic field, with which we are concerned, are far from being reliable; therefore, the assertion of the smallness of the field $H_{II\odot}$ is subject to doubt.

In this connection it may be noted that even with $H_{II\odot} = 0$ the cutoff in the spectrum by a field of the solar system can be expected. As it is known, in the Earth's orbit the field of the Sun $H_{♁} = \frac{H_{II\odot} r_{\odot}^3}{2R^3} = 1.3 \cdot 10^{-6}$ (with $H_{II\odot} = 25$ oersted) and in Neptune's orbit $H_{♆} \sim 10^{-10}$. Further, according to a well-known argumentation (see, for example [11, 15]), it can be expected that in the interstellar gas there exists a magnetic field H, determined by the relationship:

$$\frac{H^2}{8\pi} \approx \frac{\rho v^2}{2}, \quad H \approx \sqrt{4\pi\rho}\, v$$

where ρ is gas density and v is its velocity. In our solar system $\rho > 10^{-24}$ g/cm^3, gas velocity in the Earth's orbit, probably, is in the order of $v_{♁} = 3.10^3$ cm/sec, and thus, for the Earth $H \geqslant 10^{-5}$, i.e. larger than the solar dipole field.

Therefore, it is conceivable that the solar system as a whole possesses a certain magnetic moment. M_c, which can have a value on the order of 5.10^{33} gauss .cm^3, which is what is required for the observed cutoff in the spectrum. Such a moment would be created, for example, by a circular flow with the radius R equal to the radius of the Earth's orbit, with a cross section on the order of $\pi\left(\frac{R}{r_0}\right)^2$, flow density being $j = 3.10^{-7}$ CGSE. Given the concentration of electrons m 1, this means that the additional velocity of the electrons is $v = \frac{j}{en} \sim 10^3$ cm/sec.

In the field $H \sim 10^{-6}$ the density of force $\frac{1}{c}[jH]$, acting on such a flow, of of the same order as the density of the Sun's gravitational force at the distance $R = 1.5 \cdot 10^{13}$ with a gas density $\rho \sim 10^{-24}$ g/cm^3. Naturally, the problem of the magnetic moment of the solar system requires special analysis. However, in our opinion, the preceeding remarks actually justify the assumption that the cutoff in the spectrum may be connected more with the moment of the solar system, than with that of the Sun itself. Therefore, the absence of the Sun's moment, needed to account for the cutoff in the spectrum, is not a sufficient reason to reject the idea that the cutoff in the spectrum is caused by a magnetic field of the dipole type, acting from the outside of the Earth's orbit. (Note 1)

(Note 1): In a recently published work [37], as a result of the observation of multiply charged particles, it has been demonstrated that high-latitude cutoff is caused by a magnetic field. In this connection, the problem of the magnetic field of the solar system becomes of particularly great interest. (This note was made during proofreading.)

Summing up the above, we arrive at the following conclusions:

1. In the composition of the primary cosmic rays near the Earth, there is no noticeable number of electrons with an energy $E > 1.1 \cdot 10^9$ ev (to be more precise, their number is not larger than 0.6% of all primary particles).

2. With $cp = 1.0 \div 1.2 \cdot 10^9$ ev, a more or less abrupt cutoff occurs in the spectrum of all primary particles. A further experimental investigation of this zone of the spectrum is needed, but even now there is no reason to assume that the number of electrons with $E \geqslant 2.5 \cdot 10^8$ ev is more than a few percents of all primary particles, even in the case of a gradual cutoff in spectrum.

3. According to the present data, the cutoff in the spectrum of cosmic ray particles (in the first place, of protons), with $cp \leqslant 10^9$ ev, can be explained not by the absence of such particles, but rather by the effect of the magnetic field created by the magnetic moment either of the sun or of the solar system.

2. Galactic Radio Emanations and the Electron Component of Cosmic Rays

Presently available experimental data show that the galactic radio emanations in waves over 3m are basically of a non-thermal nature. In the direction of the galactic pole, thermal radiation, apparently, is negligible, even with $\lambda \geqslant 1.5$m.

The intensity of the non-thermal component, evolved in [16] in the range of $1.5 < \lambda < 16.3$m., is as follows:

$$I_\nu = \frac{2KT_{eff}}{\lambda^2} = \frac{2{,}76 \cdot 10^{16} T_{eff}}{\lambda^2} \frac{\text{erg}}{\text{cm}^2 \cdot \text{sec} \cdot \text{flow} \cdot \text{steradiom}} \approx \frac{Ac}{\nu} \qquad (6)$$

i.e. T is approximately proportional to λ^3. The values T_{eff} in the directions toward the center and toward the pole of the Galaxy are shown in Table 2 (to be more precise, Table 2 shows minimum and maximum values of T_{eff}, corresponding approximately to T_{eff} in the indicated directions).

Determining the value of the constant a in (6) from the data of Table 2 for $T_{eff\ min}$, we obtain on the average the value

$$a \approx 5.10^{-21} \frac{\text{erg}}{\text{sec.cm}^3\text{.cycle.steradian}}$$

In the direction toward the center of the Galaxy, the value a is approximately 10 times larger.

Table 2

Values T_{eff} for Galactical Radio Emanation

λ, cm	$T_{eff\ max}$ (center)	$T_{eff\ min}$ (pole)
150	1630*	88
187	2180*	128
300	5000	500
470	21000	2200
$1,63 \cdot 10^3$ = 16,3 m	175000	50000**

* In the direction toward the center of the Galaxy the radiation is partially thermal
** Relationship between $T_{eff\ max}$ and $T_{eff\ min}$ is distorted by absorption in the interstellar gas

At present, the general non-thermal galactic radiation is connected with only one mechanism, namely, the radiation of relativistic (cosmic) electrons in interstellar magnetic fields /17--19/. As to the radio-stellar hypothesis on the nature of the general galactic radiation, we must say that this hypothesis which always appeared to us very artificial and poorly founded, has now been entirely discredited through the discovery of the finite angular dimensions of discrete sources of cosmic radiation.

As was shown in /18/, the observed intensity of radiation can be sufficiently explained by assuming that there are electrons in interstellar space with energy of the order of 10^9 ev and a concentration of $N \sim 10^{-10}$ cm^{-3}, moving in the fields $H \sim 10^{-6}$ oersted. All these assum ptions appear to be entirely natural and this is a weighty argument in support of the mechanism under consideration.

An attempt may be made to obtain more detailed information on interstellar electrons from the spectral data. Namely, let us assume that the spectrum of these electrons if of the type

$$N(E)dE = \frac{K}{E^{\gamma}} dE \qquad (7)$$

and that they are moving in a homogeneous magnetic field.

Then, using the results of work/[20], we can represent the radiation intensity I_ν as follows:

$$I_\nu = \frac{1}{4\pi}\int P(\nu, E) N(E)\, dE\, dR = \frac{3K}{\pi}(2\pi\nu)^{\frac{1-r}{2}}\left(\frac{2eH}{m^3c^5}\right)^{\frac{r-1}{2}} \cdot \tag{8}$$
$$\cdot \frac{e^3 HR}{mc^2} U(r) = 1{,}29 \cdot 10^{-22}(2{,}78 \cdot 10^8)^{\frac{r-1}{2}} \cdot U(r) \cdot KR \cdot$$
$$\cdot H^{\frac{r+1}{2}} \times \lambda^{\frac{r-1}{2}} \frac{\text{erg}}{\text{cm}^2 \cdot \text{sec} \cdot \text{cycle} \cdot \text{steradian}}$$

where $U(r) = \int\limits_0 J(u) \cdot u^{\frac{3r-5}{4}} du$

H is a certain average value of the projection of the magnetic field perpendicular to the electron velocity; R is dimension of the Galaxy in the contemplated direction; P (r,E) is the energy radiated by an electron with energy E in one unit of time in a single frequency interval (for more detail see [18, 19]; and J(u) is the function, indicated in [20] and shown in Table 3

Table 3

Values of the function J(u)

u	J(u)	u J(u)	u	J(u)	u J (u)
0	0,256	0	1,2	0,036	0,0425
0,2	0,204	0,041	1,4	0,023	0,0325
0,4	0,156	0,062	1,6	0,0143	0,023
0,6	0,115	0,069	1,8	0,00855	0,0154
0,8	0,081	0,065	2,0	0,005	0,01
1,0	0,055	0,055	3,0	0,00023	0,0007

The spectrum, evidently, is regarded as uniform along the entire line of sight. Comparing (8) with (6) we see that r = 3, and we arrive at the expression

$$I_\nu = 3{,}1 \cdot 10^{-15} KH^2 R \lambda = a\lambda \tag{9}$$

where it is taken into account that

$$\int_0^\infty J(u) \cdot u\, du = \frac{\pi}{36} = 0{,}087 \tag{9a}$$

Assuming $a \sim 5 \cdot 10^{-21}$, $R \sim 10^{22}$, and $H \sim 3 \cdot 10^{-6}$, we obtain the value

$$K = \frac{3{,}2 \cdot 10^{14} a}{H^2 R} \sim 10^{-17} \frac{\text{erg}^2}{\text{cm}^3} \sim 10^7 \frac{\text{ev}^2}{\text{cm}^3} \tag{10}$$

Since the interstellar gas, as well as the sources of galactic radiation (cosmic electrons), form a nearly spherical system [11, 16], the value R, probably, can be increased several times; it is also admissible that the value H might reach 10^{-5} [from (5) we obtain a field of the order of 10^{-5} at $p \sim 10^{-25}$, $v \sim 10^{7}$]. Thus, apparently, $K_{min} \simeq 3 \cdot 10^{-19}$ erg/cm^3

The concentration of electrons with $E > E_0$ is equal to

$$N(E > E_0) = \frac{K}{2E_0^2}$$

Assuming $E_0 = 1.2 \cdot 10^9$ ev and $K = K_{min} \sim 3 \cdot 10^{-19} \approx 10^5$ ev^2/cm^3, we obtain $N(E > 1.2 \cdot 10^9 \text{ev}) \sim 4 \cdot 10^{-14}$ cm^{-3}, i.e. the concentration of electrons is equal to $3 \cdot 10^{-4}$ of the concentration $N = 1.2 \cdot 10^{-10}$ of all primary particles (with energy larger than $E_0 = 1.2 \cdot 10^9$ev) near the Earth. As we have seen in Section 1, from the data on cosmic rays near the Earth, for electrons $N(E > 1.1 \cdot 10^9 \text{ev}) < 6 \cdot 10^{-3} \times 1.2 \cdot 10^{-10} \approx 7 \cdot 10^{-13}$.

Consequently, the data on primary electrons near the Earth and on the number of electrons needed for the explanation of the observed galactic radio emanations do not contradict each other, and therefore it can be assumed that $K \sim 3 \cdot 10^6$ ev^2/cm^3. In order to have some reserve, let us assume $K = 10^6$ ev^2/cm^3 ($K = 10^6$ ev^2/cm^3, for example, with $a = 5 \cdot 10^{-21}$, $H = 5 \cdot 10^{-6}$, $R = 4 \cdot 10^{22}$) we obtain

$$N(E > 3 \cdot 10^8) = 5 \cdot 10^{-12} \text{cm}^{-3},$$
$$N(E > 10^8) = 5 \cdot 10^{-11} \text{cm}^{-3},$$
$$N(E > 10^9) = 5 \cdot 10^{-13} \text{cm}^{-3}$$

If we consider the accepted spectrum as correct up to energies of the order of 10^7ev, then we obtain $N(E > 10^7 \text{ev}) = 5 \cdot 10^{-9}$ cm^{-3}. However, radio measurements do not furnish a basis for judging the concentration of particles in this region. As can be seen from (8) and Table 3, a maximum contribution to the intensity is made by the electrons, for which the parameter $u \approx 0.6$, while the regions of values $u > 2$ and $u < 0.1$ are not essential. The parameter

$$u = \left(\frac{\omega}{2\omega_1}\right)^{\frac{2}{3}} = \left[\frac{\nu}{\frac{eH}{\pi mc}\left(\frac{E}{mc^2}\right)^2}\right]^{\frac{2}{3}} \qquad (11a)$$

with $u = 6r = r_{max} \approx 0.9r_1$, with $u = 2r \approx 5.6r_1$, and with $u = 0.1r \approx$ $\approx 0.06r_1$, where

$$\nu_1 = \frac{\omega_1}{2\pi} = 2.8 \cdot 10^6 H \left(\frac{E}{mc^2}\right)^2 \text{cycle} \qquad (12)$$

For $\lambda = 16.3$ m, $r = \frac{c}{\lambda} = 2 \cdot 10^7$, and with $H \sim 5 \cdot 10^{-6}$ the basic contribution to the radiation is made by particles with $\frac{E}{mc^2} \approx 10^3$, i.e. with $E \approx 5 \cdot 10^8$ ev. On the other hand, no significant contribution to the radiation with $\lambda = 16.3$m is made by particles with an energy $E < 2 \cdot 10^8$ ev, nor by particles with an energy $E \gtrsim 2 \cdot 10^9$ ev.

Nonthermal radiation on the 1.5m wave is basically determined by the particles with $E \approx 2 \cdot 10^9$ ev and is practically independent of particles with $E \gtrsim 8 \cdot 10^9$ ev. It can be said that the data on the galactic radiation testify to the fact that, in the range of energies $2 \cdot 10^8 \text{ev} < E < 8 \cdot 10^9$, the cosmic electrons have a differential spectrum

$$N(E) \approx \frac{10^6}{E^3} \ \text{cm}^{-3} \cdot \text{ev}^{-1} \qquad (13)$$

The conclusion arrived at is in accordance with existing results relating to cosmic rays on the Earth, even without making the assumption that the slow electrons are completely cut off by a magnetic field (as indicated in Section 1) according to presently available data, there can be not more than 4% of electrons with $E > 2.5 \cdot 10^8$ ev at the latitude of 69°; according to (13), we obtain in this instance 7%, which, keeping in mind the roughness of the calculation, cannot be regarded as contradictory to the foregoing figure.

It must be underscored, however, that the calculations made should be regarded as estimative, as it follows from the accuracy of the experimental data on radio emanations and the accuracy of their processing. Such calculations, as well as all computations concerning the theory of the origin of cosmic rays, can hardly claim a greater accuracy. This is connected, in particular, with the fact that we have considered the density of particles independently from galactic coordinates and that we have selected an average value of the field H, etc. Let us note in this connection: in the case of spectrum (13) the number of particles with $E > 10^9$ is so small and the data on the spectrum of nonthermal radiation are, relatively, so inaccurate, that, by changing the spectrum somewhat, in the region $E < 10^9$, it is evidently possible to ensure accordance with experience even assuming the complete absence of electrons with an energy $E > 1 \div 2 \cdot 10^9$ ev.

In conclusion, let us make an observation concerning the isotropy of cosmic rays. It is usually regarded that this isotropy, which occurs in experiments, can be fully explained by the "mixing" action of interstellar magnetic fields (to be more definite, we are considering that region of energies for which the effect of the solar field is not significant). In this connection, it is pointed out that the radius of the curvature of particles in the field H, which is perpendicular to its pulse p, which is equal to

$$r = \frac{cp}{eH} = \frac{cp\,(ev)}{300H} \qquad (14)$$

even at $cp \sim 10^{17}$ ev in the field $H \sim 3 \cdot 10^{-6}$ is considerably smaller than the radius of the Galaxy R ($r \sim 10^{20}$, $R \sim 10^{23}$; at $cp \sim 10^9$ in the same field $r \sim 10^{12}$ cm.) This argument actually explains, why the cosmic ray particles "forget" their initial direction and in the middle intermix in the Galaxy. However, according to the present ideas, the characteristic distance, at which significant changes occur in the direction and value of the magnetic field, is $\ell \sim 3 \cdot 10^{19} \doteq 10$ parsecs (see [11]). If this is the case, then some quasi-homogenous field must exist in the region of the order of ℓ; since for most observed particles $cp \sim 10^9$ and the radius of curvature $r \ll \ell$, there is no reason to speak about isotropy, without first making a special investigation.

It is possible that the region of the quasi-homogenous field is considerably smaller than the length $\ell \sim 10^{19}$, and that at the same time the effective transfer of energy to a particle, because of its "collision" with the magnetic field, is characterized exactly by the length $\ell \gg \ell'$ (i.e. ℓ' - the length of free path for "elastic collisions", and ℓ - for "inelastic collisions"). In anyccase, this question seems to be of a great importance and deserves a special analysis.

3. The Movement of Relativistic Electrons in Interstellar Space

As electrons move in the interstellar gas, there are both energy losses and, in some cases, energy gains. The following types of losses are possible:

1. Ionization losses.
2. Radiation losses, i.e. losses to braking radiation following collisions with other particles (electrons, protons, nuclei).
3. Losses connected with the "reverse Compton-effect" - - scattering of electrons on thermal photons.
4. Losses to braking radiation in the interstellar magnetic fields.

There are also losses of nuclear origin, but, in case of electrons, they are negligible as compared with the electromagnetic losses. We will also disregard the losses resulting from the fact that some electrons reach the stars, since this mechanism is approximately 10 orders less effective than that of braking on protons.

Energy gains by electrons may result from the following processes:

1. During collision with the "magnetized" clouds (Fermi mechanism [10])
2. Due to induction acceleration in the variable interstellar magnetic field (this mechanism was discussed by Ya. P. Terletskiy and A. A. Logunov [22], and by L. E. Gurevich [23]).
3. If we disregard the arrival of high-speed electrons from stars, nebulae (for example, shells of former super-novae), etc., the formation of high-speed electrons in interstellar space is possible only as a result of close collisions (δ -electrons) due to the disintegration of

mesons formed during the collisions of cosmic nucleons, and as a result of the generation of following collisions of charged particles with thermal photons.

Let us first examine the problem of energy losses.

Ionization losses of an electron with $E \gg mc^2$ in atomic hydrogen are determined by the expression

$$-\left(\frac{dE}{dx}\right)_{ion} = \frac{2\pi e^4 n}{mc^2} \ln \frac{E^3}{2mc^2 I^2} =$$
$$= 1.53 \cdot 10^5 \left[3 \ln \frac{E}{mc^2} + 20.1\right] \frac{ev}{r \cdot cm^{-2}} =$$
$$= 2.54 \cdot 10^{-19} n \left[3 \ln \frac{E}{mc^2} + 20.1\right] \frac{ev}{cm} =$$
$$= 7.62 \cdot 10^{-9} n \left[3 \ln \frac{E}{mc^2} + 20.1\right] \frac{ev}{sec} \quad (15)$$

where n is the concentration of atoms (atomic electrons), and the mean excitation energy I is accepted as equal to 15 ev; in the last expression the distance is measured in light-seconds.

Ionization losses due to other atoms are determined, in the first approximation, by the same formula, where n signifies the concentration of all atomic electrons. In interstellar space there is about 10% He and about 0.1% C, N, and O taken together. The contribution to the ionization losses from these atoms is respectively 20% and 1% of the losses in hydrogen, and we shall disregard them, since the concentration n for hydrogen itself is known with even less accuracy. The radiation losses will be treated below in the same way, although the effect is in this case proportional to $Z(Z + 1)$ where Z is the atomic number of the nucleus, and for He amounts to 30% of the losses in Hydrogen, while for C, N, and O it is 3%.

According to [11], the principal part of the interstellar gas, where $n \sim 0.1$, is not ionized. However, in the H II clouds of interstellar gas and between the clouds near the plane of the Galaxy, the hydrogen is almost completely ionized. In this case, "ionization" losses are as follows (n is the concentration of electrons): (Note 1)

$$-\left(\frac{dE}{dx}\right)_{ion} = \frac{2\pi e^4 n}{mc^2} \left[\ln \frac{m^2 c^2 E}{8\pi e^2 n \hbar^2} + 1\right] =$$
$$= 7.62 \cdot 10^{-9} n \left[\ln \frac{E}{mc^2} - \ln n + 74.6\right] \frac{ev}{sec} \quad (16)$$

[Note 1: In formula (16), in parenthesis, a mistake is usually made by substracting the one instead of adding.]

With n = 0.1 and $E = 5 \cdot 10^8$, the losses in (16) are twice as large as those in (15). Assuming that the principal part of the gas in the Galaxy is not ionized, we shall use formula 15 below.

The so-called radiation losses, which are connected with braking radiation following collisions [24], when shielding is absent, amount to:

$$-\frac{1}{E}\left(\frac{dE}{dx}\right)_{rad} = \frac{4e^6 n Z(Z+1)}{m^2c^5\hbar}\left[\ln\frac{2E}{mc^2}-\frac{1}{3}\right] \qquad (17)$$

and with complete shielding in non-ionized gas are equal to:

$$-\frac{1}{E}\left(\frac{dE}{dx}\right)_{rad} = \frac{4e^6 n Z(Z+1)}{m^2c^5\hbar}\left[\ln\left(191\cdot Z^{-\frac{1}{3}}\right)+\frac{1}{18}\right] \qquad (18)$$

where n is the concentration of atoms with atomic number Z. In hydrogen, when shielding is absent,

$$-\frac{1}{E}\left(\frac{dE}{dx}\right)_{rad} = 2.74\cdot 10^{-3}\left\{\ln\frac{E}{mc^2}+0.36\right\}r^{-1}\cdot cm^2 = = 1.37\cdot 10^{-16}n\left\{\ln\frac{E}{mc^2}+0.36\right\}sec^{-1} \qquad (19)$$

and with complete shielding

$$-\frac{1}{E}\left(\frac{dE}{dx}\right)_{rad} = 1.45\cdot 10^{-2}r^{-1}\cdot cm^2 = 7.26\cdot 10^{-16}n\ sec^{-1} \qquad (20)$$

Losses (19) and (20) become equal when $\frac{E}{mc^2}\sim 10^4$. When $E\sim 5\cdot 10^8$ev, the value (19) is about one and one half times larger than (20). For a completely ionized gas, the shielding can always be regarded as absent and formula (19) can be used.

[Note]: In an ionized gas, the shielding radius is the Debye radius $D\sqrt{\frac{kT}{8\pi e^2 n}}$ which for $T\sim 10^4$, $n\sim 0.1$ is on the order of 10^3 cm. Roughly speaking, we may disregard the shielding as long as the distance $r\sim\frac{\hbar}{mc}\cdot\frac{E}{mc^2}\approx 3.85\cdot 10^{-11}\frac{E}{mc^2}$ is much smaller than the shielding radius [24]. In our case $r\sim D\sim 10^3$ only when $\frac{E}{mc^2}\approx 3\cdot 10^{13}$, i.e. $E\sim 10^{19}$ ev.

In non-ionized hydrogen formula (19) is applicable when $\frac{E}{mc^2}\lesssim 10^2$, while taking the shielding into account the formula (20) should be used when $\frac{E}{mc^2}$ 10^2 (more precisely see [24]). Since we are basically interested in electrons with $\frac{E}{mc^2}$ 10^3, we shall use the formula for the case of completelshielding. This is even more justified since the difference between (19) and (20) is relatively small. For establishing a correspondence with ordinary calculations which take into account the inaccuracy of the logarithm in (18) for high elements, let us increase this logarithm by 10% (see [24]). As a result, instead of (20), we obtain

$$-\frac{1}{E}\left(\frac{dE}{dx}\right)_{rad} = 1.6\cdot 10^{-2}r^{-1}\cdot cm^2 = 8.0\cdot 10^{-16}n\ sec^{-1} \qquad (21)$$

where t, the unit of length, within which the energy of the electron decreases due to braking radiation, on the average e times, according to (21) is equal to 62 g/cm^2.

We must stress that the radiation losses, in contrast to ionization losses, are not continuous and it may be roughly considered that these losses do not occur at all along the path of the particle, but the electron looses all its energy immediately after having traveled, on the average, 62 g/cm^2. With $n \sim 0.1$, the path of 62 g/cm^2 corresponds to a time $T \sim 1.2 \cdot 10^{16}$ sec $\approx 4 \cdot 10^8$ years.

The hard photon, formed in braking the electron, practically is "out of play", since the entire thickness of the Galaxy totals approximately $10^{-25} \cdot 10^{23} \approx 10^{-2}$ g/cm^2 of hydrogen, and pair generation on such a path is negligible because of photon conversion. Due to the presence of matter outside of our Galaxy, a certain equilibrium must exist between the electron and photon components; this question may be of interest, but we are not going to discuss it here.

Energy losses, connected with the "reverse Compton-effect", are discussed in [25, 26]. Taking into consideration that these losses, as it appears, do not exceed the radiation losses, we will deal with them here only very briefly. Let us assume that the radiation spectrum corresponds to a temperature of 6000°, and, consequently, the mean energy of photons $\bar{\varepsilon} = 2.73\ KT = 1.42$ ev. According to [25], the mean energy of radiation in the Galaxy is accepted as equal to $\bar{p} = 0.03$ ev/cm^3. Consequently, the mean photon density is $\bar{n} = \frac{\bar{p}}{\bar{\varepsilon}} = 2 \cdot 10^{-2}$. The work [26] uses values 10 times larger for $\bar{p}$ and $\bar{n}$. However, considering that the cosmic rays and the interstellar gas form a spherical subsystem with a radius on the order of the radius of the Galaxy ($R \sim 3 \cdot 10^{22}$), it is natural to assume a smaller value for $\bar{p}$. This question is of but little importance, as we will see below.

In the coordinate system connected with an electron, the energy of the photon is equal to $\varepsilon' = \frac{E}{mc^2}\, \varepsilon\, (1 + \beta \cos \alpha)$, where $\beta = \frac{v}{c}$, ε is the energy of a photon in the terrestrial "system of rest" (in this system, the energy of the electron is E, and the angle between the directions of the movement of the electron and the photon is equal to $\alpha + \pi$). On the average, for isotropic radiation, $\bar{\varepsilon}' = \frac{E}{mc^2} \bar{\varepsilon}$ where $\bar{\varepsilon} \ll mc^2$ under condition that

$$\frac{E}{mc^2} \cdot \frac{\bar{\varepsilon}}{mc^2} \ll 1 \qquad (22)$$

Under this condition, the Thomson's cross-section can be accepted, as the cross-section for photons scattering on electrons

$$\sigma_0 = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 = 6.6 \cdot 10^{-25}\ cm^2 \qquad (23)$$

In practice, the (23) cross-section can be used with sufficient accuracy, until $\frac{E}{mc^2} \cdot \frac{\bar{\varepsilon}}{mc^2} \lesssim \frac{1}{4}$, which occurs for $E \lesssim 5 \cdot 10^{10}$ ev (with $\bar{\varepsilon} = 1.42$ ev).

Since we are only interested in such electrons, we shall use the cross-section (23). With $\bar{n} = 2 \cdot 10^{-2}$, we obtain a length for the course of on the order of 10^{26}cm, which corresponds to the time $T \sim 10^8$ years. The mean energy, transfered to the photon in scattering, in the analyzed case, is (with the accuracy up to a factor on the order of one) equal to

$$\Delta E \approx \frac{E}{mc^2}\bar{\varepsilon}' = \left(\frac{E}{mc^2}\right)^2 \bar{\varepsilon} = 1.42 \left(\frac{E}{mc^2}\right)^2 ev$$

$$-\left(\frac{dE}{dx}\right)_K \approx \sigma_0 \bar{n} \bar{\varepsilon} \left(\frac{E}{mc^2}\right)^2 = 1.9 \cdot 10^{-26} \left(\frac{E}{mc^2}\right)^2 \frac{ev}{cm} = $$
$$= 5.6 \cdot 10^{-16} \left(\frac{E}{mc^2}\right)^2 \frac{ev}{sec} \qquad (24)$$

As is evident from a comparison of formula (21) where $n \sim 0.1$ with formula (24), the mean losses for the braking radiation and for the reverse Compton-effect become equal only when $E \sim 5 \cdot 10^{10}$ ev, while, for example, when $E \sim 10^9$ ev, the losses (24) are 40 times smaller than the losses in (21). Both types of losses are similar in nature: they do not occur continuously, but in large portions, on the average, once in about $10^8 \div 10^9$ years. Therefore, we are not going to consider further the losses from the reverse Compton-effect, regarding them as small in comparison with radiation losses in the region of energies under consideration.

[Note] At energies $E > 10^{10}$, these losses are also of no particular importance, since they are smaller than the losses for braking radiation in the magnetic fields. [See (25)]. The increase in losses due to the reverse Compton-effect, when the electron approaches the Earth where there are many solar photons is also not significant (on the entire path from the Earth to infinity, in a column with 1 cm^2 area, there are $N = 4.5 \cdot 10^{20}$ photons [25], i.e. $N\sigma_0 \sim 3 \cdot 10^{-4}$; therefore, solar radiation must be given special consideration only in examining the electrons, which move along closed trajectories within the limits of the solar system [26]. At the same time, it seems expedient to make more precise (see above) the values of n and $\bar{\varepsilon}$ in interstellar space and thus to increase the accuracy of formular (24).

We now have to consider only one more type of losses, namely, the losses connected with braking radiation in interstellar magnetic fields. When an electron moves in a magnetic field, it looses energy

$$-\left(\frac{dE}{dx}\right)_m = \frac{2}{3}\left(\frac{e^2}{mc^2}\right)^2 H^2 \left(\frac{E}{mc^2}\right)^2 \frac{erg}{sec} =$$
$$= 0.98 \cdot 10^{-3} H^2 \left(\frac{E}{mc^2}\right)^2 \frac{ev}{sec}. \qquad (25)$$

where H, the perpendicular to the velocity of an electron, is a component of the magnetic field; it is assumed that $E \gg mc^2$.

By integrating the equation (25) we obtain

$$\left.\begin{aligned} \frac{mc^2}{E} - \frac{mc^2}{E_0} &= \frac{2e^4H^2}{3m^3c^5}\,t, \\ \frac{E}{mc^2} &= \frac{1}{1.9\cdot 10^{-9}\,H^2\,t_{sec} + \frac{mc^2}{E_0}} \end{aligned}\right\} \qquad (26)$$

where E is the energy at moment t, and E_0 is the energy at moment $t = 0$.

Ionization, mean radiation, and magnetic-braking losses of electrons are compared in Table 4. With regard to radiation losses, it should be remembered that they occur not continuously, but in large portions once every $4\cdot 10^8$ years (see above). Ionization and magnetic-braking losses, on the contrary, are of a more or less continuous nature and undergo considerable changes only during the transition of an electron from a region with one magnitude n or H to a region with significantly different magnitudes of one or both of these values.

Non-uniformity of the magnetic field produces a very tortuous trajectory of the particle; in most regions it is a spiral line winding around the force lines of the magnetic field. If the characteristic distance at which the magnetic field changes greatly, is ℓ, then the charged particle may resemble, in the first approximation, a molecule moving in a gas with a free path length ℓ. The velocity of the forward motion of the particle averages is on the order of c and with isotropy is equal to $\frac{c}{\sqrt{3}}$. The diffusion factor D can be assumed equal to $D = \frac{c}{3\sqrt{3}}$, where ℓ is the effective length, determined, strictly speaking, precisely by this relationship for D.

During time t the particle will progress in the given direction the distance

$$L = \sqrt{2Dt} = \sqrt{\frac{2c\ell t}{3\sqrt{3}}} \approx 10^5\sqrt{\ell t}\ \text{cm} \qquad (26a)$$

When $\ell \sim 10^{19}$, we find $L \sim 3\cdot 10^{22}$ (radius of the Galaxy), if $t \sim 10^{16} \sim 3\cdot 10^8$ years. After the expiration of such a period of time, the energy of the electron, according to (26), at $H \sim 10^{-5}$, will be equal to

$$\frac{E}{mc^2} \sim \frac{1}{2\cdot 10^{-3} + \frac{mc^2}{E_0}}$$

and, if $\frac{mc^2}{E_0} \ll 2\cdot 10^{-3}$, $E \sim 3\cdot 10^8$ ev, independently of the values of E_0.

Let us consider now the gain of energy. The Fermi mechanism [10] is connected with the collision of a particle with moving magnetic fields. From one collision, the particle receives energy on the average on the order of $\frac{v^2}{c^2}E$, where v is the velocity of the interstellar medium.

The average gain of energy is equal to

$$\frac{dE}{dt} = \alpha E, \quad \alpha \approx \frac{v^2}{c^2\tau} \approx \frac{V^2}{c^2}\cdot\frac{c}{\ell} \qquad (27)$$

TABLE 4.

Losses and Gains of Energy by Electrons in ev/sec (all values are rounded)

Энергия электрона, эв 1	Ионизационные потери, формула (15) 2	Радиационные потери, формула (21) 3	Потери на излучение в магнитном поле, формула (25) 4		Приобретение энергии $\frac{dE}{dx} = \alpha E$ 5	
	$n = 0,1$	$n = 0,1$	$H = 10^{-6}$	$H = 10^{-5}$	$\alpha = 4 \cdot 10^{-17}$ сек$^{-1}$, формула (30) (formula)	$\alpha = 2 \cdot 10^{-13}$ сек$^{-1}$, формула (31) (formula)
$5 \cdot 10^{7}$	$2,7 \cdot 10^{-8}$	$4 \cdot 10^{-9}$	10^{-10}	10^{-9}	$2 \cdot 10^{-9}$	10^{-5}
10^{8}	$2,8 \cdot 10^{-8}$	$8 \cdot 10^{-9}$	10^{-10}	$4 \cdot 10^{-9}$	$4 \cdot 10^{-9}$	$2 \cdot 10^{-5}$
$5 \cdot 10^{8}$	$3,2 \cdot 10^{-8}$	$4 \cdot 10^{-8}$	10^{-8}	10^{-7}	$2 \cdot 10^{-8}$	10^{-4}
10^{9}	$3,3 \cdot 10^{-8}$	$8 \cdot 10^{-8}$	$4 \cdot 10^{-8}$	$4 \cdot 10^{-7}$	$4 \cdot 10^{-8}$	$2 \cdot 10^{-4}$
$5 \cdot 10^{9}$	$3,7 \cdot 10^{-8}$	$4 \cdot 10^{-7}$	10^{-6}	10^{-5}	$2 \cdot 10^{-7}$	10^{-3}
10^{10}	$3,9 \cdot 10^{-8}$	$8 \cdot 10^{-7}$	$4 \cdot 10^{-6}$	$4 \cdot 10^{-5}$	$4 \cdot 10^{-7}$	$2 \cdot 10^{-3}$
$5 \cdot 10^{10}$	$4,3 \cdot 10^{-8}$	$4 \cdot 10^{-6}$	10^{-4}	10^{-3}	$2 \cdot 10^{-6}$	10^{-2}

Legend:

1. Energy of electron ev
2. Ionieation Losses formula (15)
3. Radiation Losses formula (21)
4. Losses for radiation in magnetic field, formula (25)
5. Energy gain $\frac{de}{dx} = xE$

where τ is mean time of free path and ℓ is the length of the free path

Under such conditions, when, despite the process of energy increase, (27), only sudden losses of energy occur (radiation losses for electrons, nuclear collisions for nucleons) with path length $\Lambda = cT$, the particles which have been "let out" into the interstellar medium with an energy larger than a certain minimum "injection energy", E_{min}, are accelerated and their spectrum is of the type (7), where

$$\gamma - 1 \approx \frac{c^2\tau}{v^2 T} \approx \frac{c^2 \ell}{v^2 \Lambda} = \frac{1}{\alpha T} \quad (28)$$

Experience shows that at $E > 10^{13}$ ev for cosmic rays (basically, it seems, protons) $\gamma \approx 2.7$. It follows that

$$\frac{c^2}{v^2}\frac{\ell}{\Lambda} \approx 1.7 \quad (29)$$

In [10] it was accepted $v \approx 3 \cdot 10^6$, $\ell = 1.2 \cdot 10^{18} = 0.4$ parsec, $\Lambda = 7 \cdot 10^{25}$ cm ($T \approx 7 \cdot 10^9$ years); The last figure corresponds to the cross-section for the absorption of protons $\sigma_{abs} = 2.5 \cdot 10^{-26} cm^2$, and the density of the interstellar medium (hydrogen) $\rho = 10^{-24} g/cm^3$; the path of protons in this case is equal to 70 g/cm^2 of hydrogen. It should be noted, however, that the accepted cross-section is not based on any special experimental foundations. For hydrogen the so-called "geometric cross-section" $\sigma = \pi r_0^2 = \pi \left(\frac{\hbar}{\mu c}\right)^2 = 6 \cdot 10^{-26}\ cm^2$ where $\mu = 275\ m_e$ - mass π - meson; the path in this case is equal to 28 g/cm^2. The lack of reliable experimental data makes it as yet impossible to analyze the significance of a path 70 g/cm^2. However, it is more correct to assume the density of interstellar medium as equal to $n = 0.1$ ($\rho \sim 1.67 \cdot 10^{-25}$ g/cm^3), hence $\Lambda = 4.2 \cdot 10^{26}$ and $T = 4.5 \cdot 10^8$ years. This value practically coincides with the "life span" for electrons, as determined by radiation losses. Following S. B. Pikel'ner [11], let us assume for interstellar gas (for its basic part, situated outside of clouds) $v \approx 5 \cdot 10^6$, which corresponds to a field $H \approx 8 \cdot 10^{-6}$. Then from (29) we obtain the value $\ell \approx 2 \cdot 10^{19}$, which seems to be factual. (See [11]). With accepted values of v and ℓ, according to (27)

$$\alpha \approx 4 \cdot 10^{-17}\ sec^{-1} \quad (30)$$

Because of the approximate nature of expression (27) and an inaccurate knowledge of all the parameters, the value (30), obviously, is only tentative; using the parameters (10), we would obtain a value about 10 times larger for α.

Another mechanism of the acceleration of particles in interstellar space is connected with induction effects [22, 23]. Considering that in the part of the Galaxy surrounding us and in our epoch the magnetic field is, on the average, increasing, Ya. P. Terletskiy and A. A. Logunov [22] arrive at the relationship $\frac{dE}{dt} = \delta E$, where $\delta \approx 2 \cdot 10^{-13} sec^{-1}$, (31) Both indicated mechanisms are functioning also in application to electrons, and therefore should be of interest to us. The energy gains according to (30) and (31) for various energies are shown in Table 4.

The fast electrons must also be formed in interstellar space as a result of collisions of cosmic nucleons with the nuclei of interstellar gas, as well as with interstellar electrons and thermal photons. Both latter effects are small, as compared with the former (nuclear collisions), which may be very significant. According to data, obtained, in the first place, from FIAN (Fiziches - Kiy Institut Akademii Nauk - Physics Institute of the Academy of Sciences) (See Section VIII in the last review [27]), electron-nuclei sprays occur during collisions of cosmic nucleons, and in each collision with $E \geqslant 2\cdot10^9 \div 10^{10}$ev approximately one $\pi^{\pm}$ -meson is formed (π^{0}-mesons are of lesser importance, since the γ-rays, resulting from their decay, will leave the Galaxy, hardly forming a pair). If we assume a nucleon path Δ, the mean number of charged mesons formed in one act is S, and the electron path Δ'. Then, in case of equilibrum between electrons and mesons, the electron concentration $N = \frac{S\Delta'}{\Delta} N_n$ where N_n is $\Delta' \sim 62 g/cm^2$ the concentration of nucleons. At $\Delta \sim 70$ g/cm^2, and $S \sim 1$; evidently, $N \sim N_n$. It is to be regretted that the insufficient accuracy of the values of Δ and S used do not make it possible yet to make a reliable estimate. However, we would like to stress that the appearance of a substantial number of cosmic electrons unavoidably follow from the above considerations of the equilibrium between the nucleon and electron components. Naturally, the mean energy of the electrons may be considerably lower than the mean energy of the protons, and generally the spectra of both components must not necessarily coincide at all.

4. The Electron Component and the Origin of Cosmic Rays

Any theory on the origin of cosmic rays must take into account the data described above concerning the electronscomponent, i.e. must explain, first of all, the absence of any considerable number of electrons with $E > 10^9$ ev. It is naturally to connect this fact with the effect of braking radiation in the interstellar magnetic fields. This effect is so small for protons, that it can be disregarded, while for electrons it is of considerable importance. As is shown in Table 4, the braking losses, even in a field $H \sim 3\cdot10^{-6}$ with $E > 10^9$, surpass the energy gain, as a result of the Fermi mechanism with $\alpha = 4\cdot10^{-17}$. Thus, if this mechanism is accepted as the basic mechanism, acting at high energies, then the absence of high-energy electrons is naturally explicable by losses in magnetic fields. The opposite opinion of Donahue [26] is erroneous and is connected with the selection of the value $\alpha = 2.5\cdot10^{-14}$, which is 100 times larger than that obtained in [10], and 1000 times larger than the most probable value accepted by us [see (30)] (See Note). Therefore Donahue's arguments [26] in favor of a circumsolar origin of cosmic rays have no foundation. Further, it is clear that the value $\alpha = 2 \cdot 10^{-13}$ taken by Ya. P. Terletskiy and A. A. Logunov [22] is inadmissible, and, consequently, the theory proposed in [22] or, at least its concrete version under consideration, does not correspond to reality.

[Note] It is erroneously asserted in [26] that the value $\alpha = 2.5 \cdot 10^{-14}$ corresponds to the values v and ℓ, accepted in [10]; actually, these values result in a 100 times smaller significance ($\alpha = 2.5 \cdot 10^{-16}$).

We do not intend to present a detailed discussion of the origin of cosmic rays in all its breadth in this article (See Note). Therefore, besides the points already mentioned, we shall limit ourselves solely to a few more remarks on the origin of cosmic electrons and other components of primary cosmic radiation.

[Note] This problem is dealt with in an article by V. L. Ginzburg written after the conference (Uspekhi fiz nauk (Progress in Physical Sciences), 51, 343, 1953) (Note made during proofreading.)

Because of the presence of ionization losses, the mechanisms of particle acceleration in the interstellar medium can operate only above a certain injection energy E_{min}. According to the data in [10], for protons $E_{min} \approx 2 \cdot 10^8$ ev; for α-particles $E_{min} \approx 10^9$ ev; for C, N, O nuclei $E_{min} \approx 2 \cdot 10^{10}$ ev; and for Fe nuclei $E_{min} \approx 3 \cdot 10^{11}$ ev. These values change little even with the more probable parameters assumed above [11] because, though the ionization losses decrease about 10 times (since $n \sim 0.1$, instead of $n \sim 1$). However the velocity of energy gain also decreases by about the same factor due to the increase in length ℓ. For electrons, as can be seen in Table 4, ionization losses equal energy gain at $E \sim 10^9$ ev. At higher energies, even in the field $H \sim 3 \cdot 10^{-6}$, the radiative losses exceed energy gain at $\alpha \sim 4 \cdot 10^{-17}$. Taking into account the known inaccuracy of the last expression, we can assume that in some region of energies $E > 10^9$ ev the electrons may accelerate. However, it appears improbable that this region could be a wide one. The fact that electrons with $E > 10^9$ ev are not found in considerable numbers near the Earth almost rules out such a possibility, although it does not exclude it (it could well be that high-energy electrons are present, but only in a very small number, as would be the case of spectrum (13); consequently, the search for even an insignificant number of electrons in the primary component near the Earth is undoubtedly of interest). The necessity of injection and the presence of various nuclei in the composition of cosmic rays afford a solid basis for the assertion that during the movement of cosmic ray particles in the interstellar medium only changes in their spectra may occur, but not the formation (primary acceleration) of their fundamental part. Primary sources of cosmic rays can be either magnetic stars (see [28]), or supernovae and novae stars (see [29, 30, 31]) (See Note).

(Note) Other possibilities, particularly the theory of the solar origin of the fundamental part of cosmic radiation, in our opinion, deserve less attention and we will put them aside. The presence of relativistic electrons in interstellar space, which has been proved by radio-astronomic data, is an additional argument against the theory of the solar origin of cosmic rays (according to that theory, the concentration of cosmic rays should be great only in the region of the solar system).

Acceleration of particles by magnetic stars apparently is possible in principle, but there is no answer to the basic question, namely: whether this mechanism is actually operating on such a scale as would provide an explanation for the observed intensity of cosmic rays. Contrariwise, as emphasized by Y. S. Shklovskiy [30], the mechanism related to supernovae has found direct experimental confirmation. The fact is that all known remnants of supernovae explosions are objects with radio emanations (radio nebulae), and the only known mechanism for this radiation is the mechanism of relativistic electrons in magnetic fields [17,18]. The number of electrons, necessary to explain the observed radiation, is of the same order of magnitude as is required to assure the observed intensity of cosmic rays (for more details see [30,31]). Therefore, the hypothesis which connects the origin of cosmic rays with the explosions of supernovae, seems to us very probable and deserving of particular attention.

The cosmic rays, formed as a result of supernovae explosions, naturally have proton, nucleon, and electron components. In principle, it is not excluded that even the particles with the highest known energies ($E \sim 10^{18}$ ev) originate in the same way. (See Note) Such particles should be very few and they might originate in the shell of a supernovae star [32]. It is, however, possible that the particles of highest observed speed have been accelerated in an interstellar medium. Experimental corroboration of this assumption is possible through investigation of the spectrum of the nuclear component at high energies.

([Note]) If the energy $E \sim 10^{18}$ ev is carried by a heavy nucleus, then the corresponding maximum energy of the proton will be on the order of $E \sim 10^{16} \div 10^{17}$ ev.

With the parameters given in Section 3, the observed spectrum with $\gamma \approx 2.7$ occurs only in the case of protons while for nuclei this spectrum must be entirely different. Actually, for nuclei, the cross-section, $\sigma_{abs} \approx \pi \left(\frac{\hbar}{\mu c}\right)^2 A^{2/3}$ (A is the atomic weight) and the path length $\Delta \sim \frac{1}{\sigma_{abs}}$ will be smaller than for protons. Therefore, as can be seen from (28), if for protons $\gamma \approx 2.7$, then for nuclei $\gamma > 2.7$, and in case, for example, of Fe nuclei, even $\gamma \gg 2.7$. Consequently, the difference in spectra of protons and nuclei at $E \gg E_{min}$ would support the Fermi mechanism. Presently available date [33,38] do not make the solution of this problem possible since the spectrum of nuclei is known only up to energies $E \sim 10^{10}$ ev/nucleon. In this region, the spectra of protons and nuclei are more or less the same ($\gamma \approx 2$). This may be regarded as evidence that the spectrum of all particles is determined, in a corresponding energy region, by the primary sources. For nuclei it cannot be otherwise since we deal here with energies $E \lesssim E_{min}$. Since, for the observed Fe nuclei, $E > E_{min} \approx 3 \cdot 10^{11}$ ev, then the primary sources must generate particles with at least an energy on the order of $3 \cdot 10^{11}$ ev (for protons this corresponds to an energy $E \sim 10^{10}$ ev).

In principle, it is possible that the spectrum of electrons, generated by a primary source, differs from the spectrum of protons. This can happen, for example, if the acceleration of particles due to the explosions of supernovae occurs during a period of considerable brightness of the star, when the electrons are strongly braked by a reverse Compton-effect. However, evaluations show that, in the case of statistical acceleration of particles in star explosions [33], the spectra of all particles are similar, but the maximum energy, at which the spectrum is interrupted, is proportional to the mass of the particle, and thus for electrons is about 2000 times smaller than for protons (See Note).

([Note]) For more details see [32] and the report of V. L. Ginzburg in the present collection (p. 258).

When electrons move in interstellar space, their spectrum changes because of braking radiation in interstellar magnetic fields (See [19]). If electrons with the energy E_0 are constantly entering interstellar space, then their number in the range $E, E + dE$ is proportional to the corresponding range $dt \approx \frac{\text{const}\, dE}{E^2}$ [see (25)], i.e. a spectrum is obtained with $\gamma \approx 2$. Let us now assume that the spectrum of injected electrons is $\frac{dE}{E^{\alpha}}$. Then

$$N(E)\,dE \sim d\tau \int_{E}^{E_0} \frac{dE}{E^{\alpha}} \sim \frac{dE}{E^2}\left(\frac{1}{E^{\alpha-1}} - \frac{1}{E_0^{\alpha-1}}\right) \qquad (32)$$

Where E_0 is the maximum energy in the spectrum. For energies $E \ll E_0$ at $\alpha < 1$ we obtain a spectrum with $\gamma = 2$; at $\alpha > 1$, with $\gamma = \alpha + 1$ (at $\alpha = 1$, $N(E) = \frac{\text{const}}{E^2}\, \ell n\, \frac{E_0}{E}$). As already indicated, for protons and nuclei in the region of energies $E \lesssim 10^{10}$ ev/nucleon, the spectrum with $\gamma \approx 2$ is determined by primary sources, for which, consequently, $\alpha = \gamma \approx 2$. Therefore, for electrons generated in a source with $\alpha = 2$, we obtain $\gamma = 3$, which corresponds to reality. This result appears to us very significant. Moreover, it must be noted that the spectrum of electrons from the high energy side must be interrupted. This can be explained by the fact that the energy of particles, generated in the source, probably, has an upper limit (see [32]), while in interstellar space the high-energy electrons not only experience no acceleration, but even loose their energy for a number of reasons.

The basic task of further studies in the field of theory consists, in our opinion, of working out of the problem of the generation of cosmic rays due to flares of novae and supernovae [30,31,32]. Having obtained the corresponding primary spectrum of various components, the scientist must follow up the transformation of this spectrum, while the fast particles are moving in interstellar space. Some data on this question are already available (See Section 3). Naturally, the development of the theory is possible only in close contact with experiments. Particularly important in this respect are radioastronomic investigations of the spectrum and intensity of general galactic radiation as well as the radiation of radionebulae (in the first place, shells of former supernovae stars). Experiments with primary cosmic rays on Earth should provide, in addition to a clarification of the problem of the spectrum of particles at high latitudes (See Section 1), the necessary ways of searching further for even an insignificant number of electrons and photons with $E > 10^9$ and of determining the spectrum of the nuclear component at high energies (with $E > 10^{12}$ ev; in this connection, see [34]).

In conclusion, let us emphasize that, with the development of radioastronomy and cosmic electrodynamics, the theory of the origin of cosmic rays has come into close association with other astrophysical problems and has gone beyond the stage of purely hypothetical conjectures. Considerable progress has been made in this field already, and one may hope that in the nearest futureiit will become even more significant.

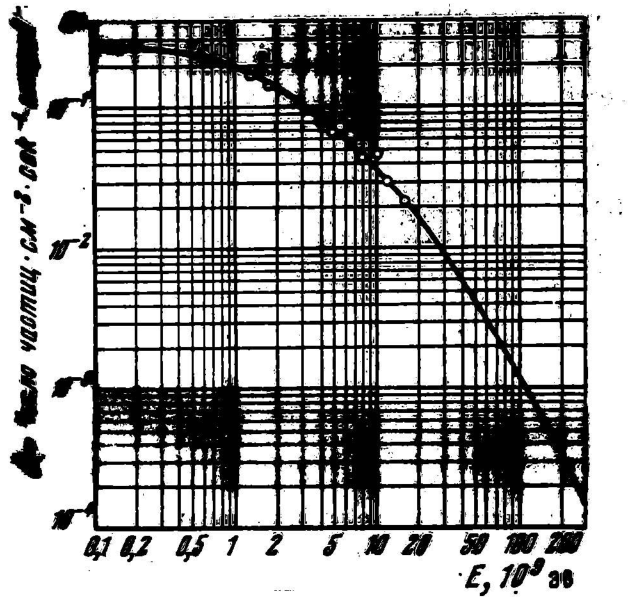

Figure 1. Integral spectrum of the primary component of cosmic rays.
Along the axis of the abscissae - kinetic energy of 10^9 ev for protons; along the axis of the ordinates - flux in vertical direction (particles X cm^{-2} X sec^{-1} X $steradian^{-1}$)
Legend:
a. Number of particles X cm^{-2} X sec^{-1} X $steradians^{-1}$).

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QUESTIONS AND DISCUSSIONS.

V. I. Veksler. I did not understand why is it, that from the fact of radiation being proportional to the square of energy, it follows that the differential spectrum becomes sharper?

Second question: If the Galaxy is really filled with electrons, can all this system then be imagined as a kind of plasma, neutral on the whole?

V. L. Ginzburg: Permit me to start with the second question. What is the picture of the distribution of cosmic rays in the Galaxy? This question was discussed yesterday in S. B. Pikel'ner's report. If we assume that the stellar population of our Galaxy forms a kind of "pancake" and the interstellar gas is distributed in a field which resembles a sphere, then the cosmic rays, which are held in the Galaxy by magnetic fields, should occupy about the same volume as the gas. The concentration of relativistic electrons, as determined directly from radioastronomic data, reaches 10^{-10} cm^{-3}, i.e. is approximately the same as the concentration of protons in cosmic rays. The concentration of the entire interstellar gas is about 0.1 to 3 times lower, and the number of relativistic particles makes up only one billionth part of the number of non-relativistic particles. Therefore, the question of neutrality should not bother us.

As to the acceleration, I am not familiar with the work of Bom, but I may call your attention to the fact that the frequency itself of the interstellar plasma is very small, and therefore, it is hard to imagine that it should be of great importance to take into account the plasma fluctuations.

I will now answer the question about the spectrum. Let us assume that you have electrons which are injected into a medium with the energy E_0 , and that they are injected continuously. The spectrum of the electrons will then be proportional to dt, i.e. to that interval of time which you have under consideration. But, since $\frac{dE}{dt} = aE^2$, it is evident that it gives a spectrum

$$N(E) = \frac{\text{const}}{E^2} .$$

Physically this is absolutely clear. The higher the energy, the greater the losses. Therefore, electrons with high energy will "live" much shorter than electrons with low energy. If the spectrum of injected electrons has the form $N'(E) = \text{const}\ E^{\alpha}$, then the spectrum will be (at $\alpha > 1$) $N(E) = \frac{\text{const}}{E^{\alpha+1}}$.

Ya. P. Terletskiy. What number do you choose for the mean energy of electrons? Where do you get that number from? Just from your theory of radiation of electrons and general galactic radiation, or from some other sources?

V. L. Ginzburg. The mean energy can be calculated on the following basis: We assume that the spectrum of electrons has the form $KE^{-\gamma}$. This expression we substitute in the expression for the intensity of radiation in a given direction. The intensity of radiation is known. We also know the relation to wave length. From the relation of the intensity to the wave length we determine γ and we obtain the differential spectrum. Thus, you know everything and in particular you know the mean energy.

Ya. P. Terletskiy. All this is connected with your theory of radiation of electrons.

V. L. Ginzburg. Everything is based on the assumption that electrons radiate in a interstellar magnetic field.

M. Ya. Pogoretskiy. At what energy value does the decline of the exponent in the energy spectrum of the electrons begin?

V. L. Ginzburg. I calculated that the losses proceed like aE^2, but actually there are also ionization losses which do not depend on E, and thus the spectrum will be somewhat different from E^{-3}. From the fact that in an experiment the spectrum has the form E^{-3}, I am inclined to conclude that the magnetic field should be of the order of 10^{-5}, rather than 10^{-6} oersted.

M. I. Podgoretskiy. How does this limit depend upon the mass of the particles?

V. L. Ginzburg. I had the same idea in mind, as you apparently have now: with very high energies (of the order of 10^{17} ev) for protons braking in magnetic fields is already considerable and it could produce an "obstruction" of the spectrum. This is very tempting! But nothing comes of it; at least not when the accelerating Fermi's mechanism is operating.

Question. This question, probably, should be addressed to S. N. Vernov, rather than to you. Once you accept the Fermi's mechanism, you thereby accept the "long life" mechanism. In the case of this mechanism you will have nuclear losses and the spectra will be different. Therefore, I would like to hear from both of you, what kind of energy spectrum of nuclei from protons to iron you actually obtain? What could we stretch here, if we should like to change the power of the spectrum in this or that direction?

V. L. Ginzburg. I entirely agree with you, but the answer to that must come from S. N. Vernov.

S. N. Vernov. In the range of energies from $2 \cdot 10^9$ to $2 \cdot 10^{10}$ ev/nucleon, $\gamma = 2$, and it is clear that this number can not change very much. In the range $2 \cdot 10^{10} - 2 \cdot 10^{12}$ ev/nucleon, $\gamma = 2.5$, and this value is the same for protons and for nuclei. At the energy $10^{13} - 10^{16}$ ev/nucleon $\gamma = 2.7$. The value γ here is really very accurate, corrections are made in tenths parts. Finally, at $10^{16} - 10^{18}$ ev/nucleon, γ is approximately $= 3$. Approximately, that means most probably somewhat smaller than 3, but no assurance can be given in this case.

V. L. Ginzburg. The question was posed concerning nuclei; does not their spectrum become obstructed at certain energies?

S. N. Vernov. So far we do not have final data concerning the spectrum of nuclei in the range of high energies. In the report by S. N. Vernov, G. T. Zatsepin, M. I. Fradkin (see p. 61) it was indicated that G. T. Zatsepin advanced the idea about the splitting of nuclei by photons of low energies, which might make it possible to separate nuclei from the full flux of particles. Preliminary data show that this phenomenon can explain the correlated broad atmospheric cascades. On the basis of these data, it may be affirmed that the heavy nuclei are also present in the range of very high energies.

Question. You said that you assume the presence in interstellar space of relativistic electrons. I am interested to know where they come? My understanding is that, if there are thermal electrons in the interstellar gas, they are evidently accelerated by some kind of mechanism to a certain energy.

V. L. Ginzburg. I believe that the Fermi mechanism or any other equivalent mechanism for acceleration in the interstellar medium can not by itself lead to the appearance of a large number of relativistic particles. Fermi advanced the idea that protons can regenerate. But there are nuclei which cannot regenerate; therefore, it is improbable that protons could regenerate either. I am of the opinion that there are primary sources and the role of the medium is to cause certain changes in the spectrum, I presume that this role is not very great and may even be entirely insignificant.

Your question allows to make one remark. Let us analyze the process of the disappearance of protons. A proton lives about $4 \cdot 10^8$ years. It disappears in collision with another proton. From this originate the mesons. $\pi^{\pm}$ mesons disintegrate into μ mesons and the latter into electrons. π° mesons disintegrate into gamma rays which leave the Galaxy. If, on the average, about one particle is generated, as follows from the data on electron-nuclei cascades, then we must conclude simply from equilibrium considerations that electrons are produced in approximately the same number as protons. Thus, from these simple considerations it follows that there must be electrons in interstellar space, and that they must be comparable in number to protons. Naturally, the spectrum of decay electrons must be softer than that of protons.

S. N. Vernov. In this connection, a question: is it not true that the electrons originating as a result of nuclear collisions will have an energy which is less by about one order? Therefore, γ will not be the same as you have said.

V. L. Ginzburg. I would not like to be understoon as having said that all electrons are produced as a result of nuclear collisions. I believe that only a part of the electrons is generated in this way. Any source must also produce electrons. But in the total number of electrons, the generation of electrons can play an important role which has to be taken into account. The problem of the spectrum of secondary electrons needs special analysis.

G. B. Zhdanov. The question was raised here of what can be said about the spectrum of heavy nuclei in connection with the Fermi mechanism. So far, very little is known about the spectrum of heavy nuclei. However, should the Fermi hypothesis be correct, the power of the spectra must be so much different for protons and heavy nuclei, that even those rare observations, the little material which is already known, provide the basis for an assertion that there is apparently no great difference between the spectra.

V. L. Ginzburg. This is rather an answer than a question. I believe that it is very important to clarify what the nature of the energy spectrum of nuclei is. If it can be established that this spectrum is the same for nuclei and protons, then this would speak decisively against the Fermi mechanism. I did not insist, at all, on the Fermi mechanism.

G. B. Zhdanov. You are saying that the Fermi mechanism is not essential for you, that it accelerates only in the range of high energies. But when you speak about the selection of the constant $\alpha \sim 10^{-16} \div 10^{-17}$, you are then taking into account the possibility of acceleration.

V. L. Ginzburg. From the data on the electron component we can put a certain upper limit on α (the constant α can not be larger than 10^{-16}). If it is larger, then it is bad. It may well be smaller. If it is sufficiently small then the Fermi mechanism will not be effective. Naturally, if the spectrum does not depend on Z, then this will indicate that the Fermi mechanism is inoperative.

Question. It may be assumed that there is some other mechanism, and not Fermi's mechanism, in the interstellar medium. Then it must be regarded that this is a really effective mechanism which accelerates the particles very fast. Consequently, α must be at minimum on the order of 10^{-15} or somewhat more. This sets the limit for the value α from the other side. Thus, you haver a contradiction here.

V. L. Ginzburg. I don't think there is any contradiction here. If the radio emanations give an indication that α cannot exceed a certain value, then this puts on upper limit on the α value. But if the α value is sufficiently small, then the radio emanation is all right, and the Fermi mechanism is not operating effectively at all. We will speak about how the acceleration occurs tonight. All I want to say at present, is this: we must take into account the requirement which is connected with spectrum of the electrons, insofar as this requirement is not imagined, but is based on the observations indicated above. It must be taken into account, so that the theory should never contradict experience.

A. A. Korchak. In 1948 an article was published by Finberg and Primakov concerning collisions of electrons with light quanta. What do you think, were their calculations erroneous or not?

V. L. Ginzburg. There was another work on this theme. We took this effect into account. Various versions were considered and it appeared that the losses of those electrons in which we are interested (with energy not exceeding 10^{10} ev) are very small, even smaller than the braking losses. Undoubtedly, if the losses were large, the Finberg and Primakov effect would be very interesting, but since this is not the case, we did not analyze it in more detail. This effect would be of interest for the solar theory of the origin of cosmic rays, because, if the electron moves in the vicinity of Sun, it should meet many photons on its way and the energy losses might be considerable.

Ya. P. Terletskiy. I will make only a few remarks.

As has already been said by V. L. Ginzburg, all the theory developped by him is based on the assumption that the radio emanations of the Galaxy result from electrons. This assertion was expressed in one of his earlier works.

However, nothing was said here about other possibilities. We were, in particular, discussing another possibility, namely, that protons may radiate while moving in magnetic fields. True, it appeared that radiation must come basically from protons with very high energies. But even at very high energies they radiate sufficiently and give the spectrum which is demanded on the basis of the measurement of radio emanations. Consequently, another mechanism of radiation is also possible. In any case, we have shown that cosmic protons will radiate at the spectrum limit as well as electrons with the same energy and approximately with the same intensity. More detailed information will be given on that by A. A. Korchak, who has dealt specially with this problem. Thus, there can be reasonable doubts about V. L. Ginzburg's argumentation. Moreover, it is not known how electrons with energies of the order of 10^8 ev could appear or where they would come from?

V. L. Ginzburg. asserts that with the values of α, which we are using in our theory for the mechanism of acceleration which is somewhat different from Fermi's mechanism, the electrons should be intensively accelerated by Fermi's mechanism, since even with small initial energies ionization losses would be compensated by intensive acceleration. Thus, the objection against a large α is based on the thesis that relativistic electrons exist everywhere, while this assertion in turn is deduced from the idea that radio emanations are to be explained by the universal dispersion of relativistic electrons. But, if instead of this hypothesis we accept the assumption that the electrons, as well as the protons, are originally injected into interstellar space by some kind of accelerators from some stars, as I have proposed in my report, then it is not at all evident that electrons can appear generally with an energy on the order of 10^8 ev. Indeed, if the primary sources, as was indicated, are emitting protons with the energy 10^8 - - 10^9 ev, then the electrons must be emitted by these sources with a much lower energy because any primary source must necessarily radiate the same number of electrons and protons, and, consequently, the electrons and the protons must have the same average velocity or charges would be accumulated in the source. If protons and electrons have the same velocity, then, correspondingly, the electrons have considerably lower energy than the protons. This has already been pointed out by Johnson. (T. H. Johnson, Rev. Mod. Phys, Vol 11, 1939, page 208.) Therefore, if a primary source is radiating protons with the energy 10^9 ev, then it radiates electrons of much lesser energies.

The conclusion about the absence of high-energy electrons is based not only on general considerations, according to which there is some sort of a ban on the radiation of high-speed electrons, but also on studies of the mechanism of the induction stellar accelerator.

Let us take, for example, an accelerator with non-coinciding axes of rotation and magnetic moment; no doubts were voiced that its calculation was done by us. How does the acceleration process operate in this accelerator? Because of electromagnetic induction in the surrounding space, an electric field is formed. In the region far from the star's surface, where the length of free path is sufficiently great, the electrons and ions behave as if they were free. We can regard their motion as the motion in electric and magnetic fields, existing in an inertial system of calculation. In the immovable system of calculation the electrons will move, just like protons (ions) by winding along the magnetic force lines. They can escape into the space of the universe if the radius of the spiral is sufficiently large. It appears that with the same initial energy the radius of the spiral of an electron is considerably smaller than that of an ion. Therefore, those ions are easily detachable which, ever accelerating, move along the lines, not to far removed from the star, i.e. where they can accumulate great energy. On the other hand, the electrons will detach themselves only in those cases, when they depart from the star along the force lines which terminate somewhere around the pole. In this case, however, they will accumulate little energy. Thus it follows even from this theory that electrons must detach themselves with less energy than the protons.

Other mechanism can be considered, for example, those with magnetic spots or with the variable momentum of the star. These were thoroughly analyzed by us. In all of them, electrons will depart with less energy then protons.

Consequently, there are good reasons to doubt V. L. Ginzburg's basic proposition which explains general radiation on the basis of relativistic electrons. Radio emanations can be successfully explained as the radiation of ultrarelativistic protons. True, difficulties arise in our theory in explaining the intensity of the radio emanations if it is assumed that the sources of radiation are situated within the Galaxy.

But, if one assumes that the sources of radiation are distributed over the entire Metagalaxy, those difficulties can be eliminated.

I believe that, working farther in this direction, we could really explain the radio emanations of the Galaxy by the radiation of protons, and at the same time provide for an acceleration mechanism with a large value α.

A. A. Logunov. The report contained a remark that so far there are no reasons to regard the energy spectrum of the proton component as coinciding with the energy spectrum of ion component in the case of very high energies. However, we can point to experimental work, published in 1952, where it was shown that the spectrum of the proton component coincides with the spectrum of the α-particles up to energies of 10^{14} ev inclusively. So far, no experiments in the range of energies exceeding 10^{14} ev have been undertaken. At the same time, if we do not make the assumption that the acceleration time is much shorter than the life of the particles, then we will obtain for the spectrum exponent for α-particles $\gamma \sim 5$, which is different from the spectrum exponent of the proton component. Therefore, it can be reasonably assumed that, if a mechanism of interstellar acceleration operates the mean acceleration time is much shorter than the life time of the particles.

In conclusion, I would like to express the wish that this conference discuss in more detail the problem of turbulent motion of the interstellar medium.

I. S. Shklovskiy. The report which we just heard is of great interest. There is no question that the interpretation of the radio emanations of the Galaxy opens a new page in the study of the problem of the origin of cosmic rays and, not only of the origin, but also of the nature of the primary component of cosmic rays in general.

Doubts have been voiced here concerning the reliability of these data. To what degree is it permissible to interpret the radio emanations of the Galaxy, as due to the braking radiation of relativistic electrons in weak interstellar fields? The following must be said concerning this question: every attempt to consider the sources of galactic radiation as separate discrete objects, necessarily leads to the conclusion that the number of such object in the Galaxy must be exceptionally large, fantastically large, inacceptably large. Therefore, we must necessarily accept the fact that the radiation sources are distributed continuously in interstellar space. Then the number of possibilities is not so great. We know that undoubtedly thermal radiation of the interstellar gas occurs. This radiation is observed and it can be isolated, but it is significant only for galactic latitudes which are not too high. Thermal radiation of interstellar gas plays a role only in the vicinity of the galactic equator. What then is the nature of the radiation at great distances from the galactic plane, where there are no clouds of interstellar medium, where the stellar population is to a significant degree rarified? The answer to this question is provided by the contemporary ideas on the nature of the galactic gaseous interstellar medium and of the interstellar magnetic fields. These new ideas on the nature of the interstellar medium, which were expounded in the report of S. B. Pikel'ner, appeared a year ago. Their development proceeded in parallel with the development of our ideas on the nature of cosmic radiation and both ideas combined in a surprising manner giving support to one the other. And thus, the basic ideas on interstellar magnetic fields, on the characteristics of the interstellar medium, and on the cosmic rays are combined into a single complex.

The possibility of interpreting the radio emanations of the Galaxy in the manner indicated here by Ya. P. Terletskiy still remains. However, great difficulties arise with this interpretation. Indeed, we will have in this case "to stuff" our Galaxy with such a quantity of relativistic heavy particles, that their total energy would be great beyond imagination. Consequently, if we assume that the radio emanations are generated by "superenergetic" heavy particles, then the density of energy will become of incredible magnitude, which constitutes an insurmountable difficulty.

I will now turn to some questions connected with the report of V. L. Ginzburg.

Already existing information on cosmic radiation makes it possible for us to draw a number of very important conclusions concerning the nature of the particles of the cosmic rays in the interstellar medium, mainly, concerning their distribution in space.

First of all, such questions arise: can any concentration of cosmic particles occur toward the galactic center? Have the sources of cosmic radiation any concentration toward the center? In that case, when the diffusion time through the clouds of the interstellar medium is less than the life time, which is determined by the energy losses, it is easy to convince oneself that the cosmic rays particles must fill the interstellar medium with practically a uniform density. Local fluctuations, naturally, are possible, but there should be no systematic trend toward a localization toward the center. If this is so, then the data on the distribution of radio intensity (brilliance) over the sky make it possible even not to construct a rough model of the distribution of cosmic rays in our stellar system. Roughly speaking, the cosmic rays and the magnetic fields within which they are moving fill the elipsoid of rotation, the large axis of which is about 10000 parsec, and the small one about 5000 parsec. Observations prove directly that this picture corresponds to reality. Let us assume that a certain concentration of cosmic ray particles occurs toward the center. This would mean that during the time when the particles are being diffused from central regions toward the periphery, they should already lose a considerable part of their energy. But in this case the electrons in the central regions of the Galaxy would possess, on the average, greater energy than those in peripheral regions. This would undoubtedly be reflected in the spectrum of radio emanations. Radiation with comparatively high frequencies would predominate in the central region of the Galaxy. Meticulous comparison of existing data on the spectrum of the component of radiation resulting from the braking radiation of relativistic electrons in different regions of the sky, after eliminating the gas component, clearly show that within limits of 10--15% there are no divergences in the spectra. This means that the diffusion time is considerably shorter than the time for substantial energy losses, and that the cosmic ray particles fill the entire indicated region with constant density.

<u>L. E. Gurevich</u>. I want to make two remarks. One remark concerns the turbulence of the interstellar medium. The problem of the turbulence of the interstellar medium has been thoroughly investigated in recent times, which is evident, in particular, in the report of S. B. Pikel'ner. The presence of magnetic fields in the interstellar medium decreases its compressibility because compression intensifies a magnetic field and increases energy. Compression therefore requires additional work. For this reason, the turbulence may be regarded as turbulence of an almost incompressible medium. Consequently, for turbulence of a sufficiently small scale we can apply the relationships obtained for isotropic turbulence, i.e. Kolmogorov's Law.

Second remark. As is known, Fermi's mechanism of acceleration required that the product $u^2 \cdot \frac{1}{\ell}$ have some strictly determined value. Actually, however, both its constituent parameters are undoubtedly subject to very considerable fluctuations. Therefore, in all discussions concerning the application of Fermi's mechanism and in comparing the theoretical deductions with observation data, we must keep in mind the existence of considerable fluctuations of these parameters and the resulting possibility that these fluctuations will lead to something, like superimposing many power laws. Naturally, it is always possible to accept the value $\frac{d \ln N}{d \ln E}$, as an effective power exponent, but the presence of fluctuations alone will already cause some changes in the effective power exponent, which are connected with the changes in energy.

Hence it follows that, in order to compare the actually observed changes of this exponent with the theoretical deductions, we must first eliminate from those theoretical deductions the influence of fluctuations of both the parameters comprising the Fermi mechanism on the changes in the power exponent.

<u>A. A. Korchak</u>. I would like to make some remarks in connection with the questions posed by me. The main difficulty of the proposed point of view is, in my opinion, connected with the assumption of the

of the presence in the interstellar gas of electrons with the density of $5 \cdot 10^{-11}$ particles /cm^3. I regard it as necessary to review once more the calculations of Finberg and Primakov. As far as I remember, they consider in their work cases of collisions of relativistic electrons (with energies up to 10^{11} ev) with light quanta both throughout the entire Galaxy, and in the vicinity of Sun. The probability of collision with light quanta during the rectilinear motion of an electron from infinity to the Earth's orbit is estimated by them as approaching one. On this basis, the conclusion is made in the article that there can not be electrons with the energy observed in cosmic radiation in interstellar space. If we add to this that the presence of magnetic fields in interstellar space will make electrons wander a long time in the Galaxy, then the indicated conclusion of Finberg and Primakov, if it is correct, will be even more founded.

Now, one more remark. I am more accustoned to the following formula for radiation of charged particles (A. A. Korchak and Ya. P. Terletskiy, ShETF (Journal of Experimental and Theoretical Physics) Vol 22, 1952, page 507.):

$$dW = \frac{3\sqrt{3}}{4\pi} \frac{e^4 H^2}{m_0^2 c^3} \left(\frac{E}{m_0 c^2} \right)^2 y \, dy \int_y^\infty K_{5/3}(x) \, dx$$

If the direction of particle velocity makes a certain angle with the direction of the intensity of the magnetic field, then this formula is not correct, and a more general expression must be taken as a basis. However, we can approximately estimate the influence of the indicated angle on the general energy and the radiation spectrum. Since the energy of the particle enters in the above expression as a square, the radiation energy will depend to a great degree on the sine of this angle. In this case, for example, all particles, whose velocity of motion makes less than a 30° angle with the direction of intensity will radiate by one order less.

Much greater difficulty arises in calculating the spectrum. While in calculating the total energy we may take averages corresponding to angles, we, naturally, cannot do that in calculating the spectrum. Therefore, the dependence on the angle must substantially affect the nature of the spectrum. It can be said in advance that there will not be such good correspondance between the electron radiation spectrum and the radio emanation spectrum.

And now a few words about the general energy of cosmic radiation. If we proceed from the data on the flux of cosmic ray particles near the Earth and do not assume that in other regions of the Galaxy the density of cosmic radiation may be considerably different, then the general energy of cosmic radiation amounts to on the order of 10^{55} to 10^{56} erg. Rough estimation shows that this magnitude of energy is greater than the energy of the thermal motion of interstellar gas and of the kinetic energy of the motion of the interstellar magnetized "clouds", and is of the same order of magnitude as the energy of the explosions of novae and supernovae stars for 10^{11} years and the kinetic energy of the motion of the stars. Two conclusions can thus be made. The first conclusion: in the development of all cosmogonic hypotheses, particularly the hypothesis of L. E. Gurevich and A. I. Lebedinskiy, cosmic radiation portion cannot possibly be left out of the total energy balance. Second conclusion: in considering the energy balance of the Galaxy, we must keep in mind that there is, evidently, a transformation of cosmic ray energy into thermal energy.

In trying to explain the phenomena of the isotropy of the primary component, it is usually assumed that the magnetic fields increase the paths of cosmic ray particles and the latter, having wandered a posited time, "perish" inside the Galaxy. It can be considered that all the energy of cosmic radiation is conserved basically within the Galaxy. This fact was noticed by Unzol'd who connected it with an explanation of isotropy. From this point of view, it can be said that the energy of cosmic rays is transformed into thermal energy; the thermal energy is transformed into the energy of the arising turbulent flows, and, due to the Fermi mechanism, or the mechanism described at this conference by Ya. P. Terletskiy, finally is again transformed into the energy of cosmic rays.

It is hardly possible to give a more detailed picture at present, but one point is absolutely certain, i.e. when constructing cosmogomic hypotheses, one cannot leave out of the total energy balance the energy of cosmic radiation and disregard the fact that this energy is being transformed into other types of energy inside the Galaxy.

V. L. Ginzburg. I will deal first with the problem of the radiation of protons. In my first article on this topic, which is known to Ya. P. Terletskiy, it states as follows: "As it will be shown below, the assumption that there is radiation of protons, is unrealistic and will not even be discussed here in more detail". Actually, however, this possibility was considered. The radiation of protons is comparable to the radiation of electrons if the energy of the proton is $3 \cdot 10^6$ times greater than the energy of the electron. Even if it is taken into account that the energy spectrum of protons is somewhat different from that of electrons, still the observed radiation could only be produced if the density of protons with an energy on the order of 10^{14} ev were of the order of $10^{-10} cm^{-3}$, while actually it is five orders less.

Now concerning the remark of Ya. P. Terletskiy, where he says that, perhaps there are no electrons at all. I decisively refute the objection connected with protons because to assume that protons radiate is much worse than to assume that electrons radiate. It is a different matter that there is a hypothetical element in the theory, as was stressed in the report and was said at yesterday's meeting. In principle, there may be some other mechanism of radio emanation which is unknown to us. Nothing can be said in the regard at present.

As to the remark of A. A. Korchak, - this remark is correct, and it must be considered that the formula (25) includes the value of the perpendicular component of the field and not the value of the field itself. I agree that a more detailed calculation would be efficacious. But we are speaking here about the factor of the order of one, and it is impossible anyway at present to work with greater accuracy in this field. Moreover, we can select real data, to which the astronomers will not object and this selection will result in lowering the necessary density of the electrons by 10 times, making it no longer $10^{-11} cm^{-3}$ but $10^{-12} cm^{-3}$. The calculations of Finberg and Primokov to which A. A. Korchak referred were checked and it was shown that the effect was small. Donahue also says that only movement along a closed orbit near the Sun can brake an electron.

What was said by V. I. Veksler about the acceleration and plasma is interesting and this problem should be studied further.

In reference to the remarks of A. A. Logunov that the spectrum of complex nuclei can be determined from the available experimental data. We still don't know, what the form of the spectrum is at high energies. In Kaplon's article, to which Logunov refers, only two energy -particles are described. It is impossible to determine the spectrum from just two particles. More detailed data are lacking at present. I would like to stress once more, however, that I am not expounding Fermi's mechanism here and not presenting a complete scheme for the origin of cosmic rays. If Fermi's mechanism is rejected, then it must be reckoned that the fast particles are generated by primary sources.

Fermi's mechanism is a hypothetical one, but the fact that there are notelectrons, is a fact which imposes specific limitations on the admissible mechanisms of interstellar acceleration.

A few words on the remark of L. E. Gurevich about the Fermi mechanism. Obviously, the theory of Fermi's mechanism in the form in which it was presented by Fermi, is only a beginning. The acceleration depends upon the following parameter: $\frac{u^2}{\lambda}$ (the ratio of the square of the velocity of the non-uniformity to the size of the non-uniformity). It is entirely clear that some turbulence spectrum exists. If the Kolmogorov spectrum is accepted, then a definite conclusion can be drawn. In any case, there is no doubt that some spectrum is included. This spectrum is known only for non-uniformities of large dimensions. We have here a magnetohydrodynamic case, while the Kolmogorov spectrum refers to ordinary hydrodynamics. What role is played by the magnetic field and how the magnetic field changes the spectrum, we don't know and this is a very important question. There are some indications that

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the spectrum changes only insignificantly; then, possibly, it can be used. However, I want to emphasize that in the future we will have to go considerably farther: to analyze more correctly and in more detail the path of the movements of a particle in a turbulent medium, taking into account the spectrum of the turbulence, etc.

In concluding this discussion, I would like to point out once more the basic idea of our investigation. We observe the radio emanations of the Galaxy and we strive to explain them. There was an alternative hypothesis of "radiostars". It was thought that there were a great number of "radiostars", which were invisible, but gave off great radio emanations. There was always opposition to this point of view, but only observations could definitely resolve the question. Observations have now refuted the radiostar hypothesis. Since this is so, the only available explanation of galactic radio emanations is the radiation of relativistic electrons in the interstellar magnetic fields. Therefore, I believe, we are entirely justified in proceeding this way and in developing the theory precisely in this direction. Under such conditions, there is simply nothing else to do.

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